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APPLICATION OF ADAPTIVE CONTROL SYSTEM FOR SATELLITE NAVIGATION OPTIMIZATION USING NEURAL NETWORK

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Abstract

Satellite Attitude Determination and Control Systems (ADCS) are critical for maintaining satellite stability and accurate orientation while in orbit. This paper focuses on the Nigeria ThinSat-1A and addresses challenges posed by nonlinear disturbances, particularly electromagnetic torque, which can destabilize the satellite's angular velocity and orientation. To mitigate these effects, a Multi-Layered Neural Network (MLNN) was employed to develop an Adaptive Control System (ACS). Real-world data from the NigeriaSat-2 system at NIGCOMSAT were collected to train the MLNN-based ACS and to model the satellite's dynamic behavior for optimized control. The system was implemented and evaluated using a Helmholtz cage for geomagnetic field simulation and further refined on a hardware testbed. Additionally, vector data were utilized to estimate satellite orientation through a fast and reliable Attitude Determination Algorithm (ADA). The performance of the ACS was validated using Simulink with aerospace and neural network toolboxes. Results demonstrated that the ACS effectively minimized the impact of nonlinear dynamic torques, maintaining satellite stability and providing precise angular velocity control over multiple orbits.

Keywords: Satellite Attitude Control; Adaptive Control System; Multi-Layered Neural Network; Attitude Determination Algorithm

1. INTRODUCTION

The level of electromagnetic torque which is generated by the actuator of a spacecraft contributes to disturbance on the stable orbiting of satellites and has remained a major challenge over the years, resulting to poor precision and navigation performance (Carlo, 2002). The conventional control systems employed for attitude determination and control aimed at solving these problems suffer delay response time to identification of dynamic torque and minimizing it's the impact on the angular velocity (Klaus, 2018). Hence there is need or an adaptive control solution which will helps solve these technical problems and ensure that satellite navigate with high precision (Virgil-Llop et al., 2019).

The attitude of a spacecraft is its orientation in space, and the term attitude determination refers to the entire process of estimating attitude, which includes the use of directional sensors in conjunction with state estimation techniques (Yuri, 2020). Attitude determination is a critical aspect of most satellite missions, and a wide variety of sensors and estimation algorithms are readily available for use in an attitude determination system (ADS).The traditional approach to attitude determination utilizes relatively large sensors in conjunction with high tolerance pre-flight alignment and calibration procedures. (Inamori et al., 2011).

A correspondence satellite is a gadget that speakers Radio Recurrence signal through a transponder (an incorporated beneficiary and transmitter of radio signs) (Nguyen et al., 2018). It makes a correspondence channel between a source transmitter and a collector at various areas on Earth. The reason for correspondences satellites is to hand-off the got signal around the bend of the Earth permitting correspondence between broadly isolated focuses (Alexandre et al., 2016). This is basically done by mirroring the radio wave shipped off the satellite from the sender back to the collector a way off and for this reason, the satellite is dined into a huge span over the earth surface (Assaad et al., 2014).

As per Reyhanoglu and Drakunov (2018)their examination on Mentality Assurance for Little Satellite with Infrared Earth Skyline Sensors, which presents an insightful methodology that is intended to create an expected worth of the nadir vector in the body edge of the satellite from the World's viewpoint sensor development. Miniature estimated Microwave Environmental Satellite (MicroMAS) was utilized to survey model of sensor readings in light of Earth skyline location. The affectability examination of this framework was directed which introduced about 0.13 opposition mistake and which is identical to 10km position information blunder. Thus, an improved work to lessen this mistake rate is needed for a more exact framework.

Alexandre et al., (2016) distributed an exploration work on Mentality Assurance and Control Framework for a GNSS-R Earth Perception 6U CubeSat Mission. This work portrays the demeanour assurance and control framework Attitude Determination and Control (ADCS) of Feline 2 which is a six-unit CubeSat. These targets controlling the satellite in circle and satisfying the prerequisites fundamental for the satellite framework. Feline 2 is utilized to guide the receiving wires towards the earth toward perform tests and afterward situate the sun-oriented boards towards the sun to expand the force input when the battery level is low. Cullen (2016) introduced an exploration work on Direction, Route and Control of Little Satellite Demeanor Utilizing Miniature Engines. This work manages the plan, improvement and combination of a Direction and Control (GNC) subsystem into a unique system that can be executed on-board progressively to perform satellite demeanor controls by telling the precise speed increase dependent on a fourth-order polynomial regarding time. The rate blunder rate distinguished for this examination was recorded to be 15% overall. Thusly, future attempts to diminish this mistake rates are vital for a more solid framework.

From the study, it was observed that many research has been developed to improve the attitude and control of satellite systems, however despite their success solutions have not been obtained which considered the dynamics of electromagnetic torque and its impact on angular velocity satellites during orbiting. This has remained a gap and will be addressed in this research using adaptive control system. This research is aimed at attitude determination and control of ThinSat system using adaptive control technique.

2. DESIGN METHODOLOGY

The methodology of design involves the collection of data from the Nigeria ThinSat 1A system to discover the attitude and technical challenges. Then the model of the attitude control system was developed and the data of the spacecraft dynamics collected considering the attributes of navigation such as position and speed and trained with an adaptive control system to get a reference point for adjustment and control instability. The system developed was implemented using a high-level programming language and integrated on the testbed for optimization.

2.1 Data Acquisition

The collection of data for the system was from the NigerianSat-2 system at the Nigerian Communication Satellite Limited (NIGCOMSAT), Abuja. The collected data was directed to determine the impact of dynamic torque on the satellite system using the test facility in Figure 1 and considering key performance indicators such as torque, angular velocity, error in angular velocity and time of the system.

From the test facility, the Helmholtz cage was used to provide three axis dynamic magnetic field which will cancel the earth magnetic field and create a geomagnetic field-based environment similar to space for satellite habitation. The Attitude Determination and Control (ADCS)hardware is the satellite control system developed with Proportional Integral Differentiator (PID) control system which was used to control the attitude parameters of the spacecraft towards desired orientation. The test control system software used is the space mission control software which has the capacity to monitor the dynamic behaviour of satellite and reported to a monitoring laptop. The motion tracking system is a horn antenna which is specialized in tracking the torque, angular velocity of satellite, while the sun simulator is used to provide up to 50,000lux illumination and can be adjusted from 30 to 100 percentages. The air bearing platform is used to introduce nonlinearity in the environment and then test the control attitude of the satellite system. To test the ADCS control performance, the air bearing was used to induce atmospheric pressure via pressurized gas in the environment to allow the control system to function at zero gravity. The pictorial diagram of the satellite system is presented in Figure 2.

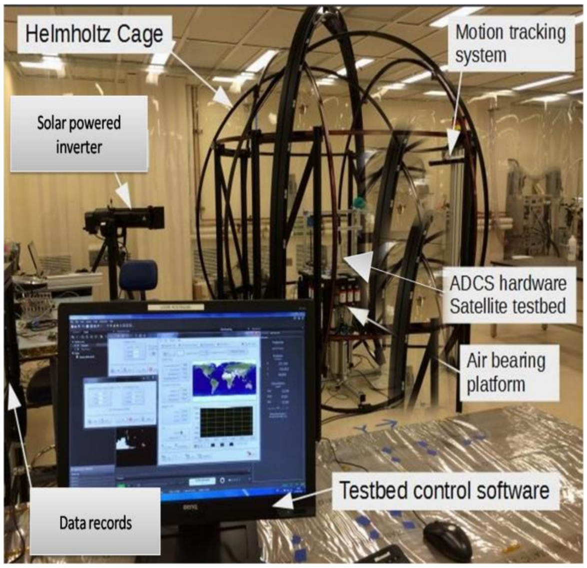

Figure 1: Image of the Test facility (Courtesy: NIGCOMSTAT)

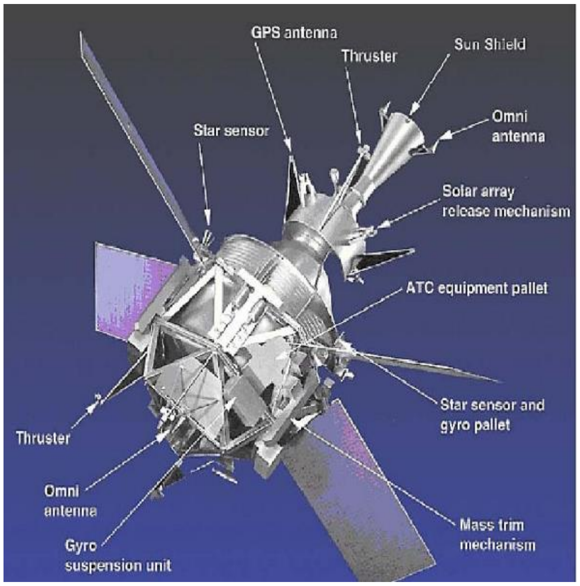

Figure 2: Picture of the NigeriaSat-2 (Source: NIGCOMSAT)

The Figure 2 presented the picture of the satellite system under study. The diagram showed the various components such as the sensors, antenna, gyroscope, etc which were used to construct the satellite system. The features of thedata collection process of the ADCS was reported in Table 1.

The Table 1 presented the attitude and control attitude of the spacecraft characterized. From the result it was observed that the dynamics from the electromagnetic torque which applied the drive force resulted to error in the angular momentum presented by the x, y and x data respectively.

Table 1: Features of Data Collected

Year	X (m)	Y (m)	Z (m)	x(mm)	y (mm)	z (mm)	N
1	6202492.807	822088.724	1225614.669	11.9	9.0	6.4	258
2	6202492.802	822088.756	1225614.687	12.0	14.0	7.6	221
3	6202492.792	822088.775	1225614.705	11.9	12.2	7.6	225
4	6211960.221	459265.512	1268115.070	12.0	9.1	6.2	257
5	6211960.228	459265.528	1268115.090	14.2	15.1	11.7	221
6	6211960.218	459265.558	1268115.115	12.4	15.6	6.2	250
7	6287174.200	922979.505	546712.811	14.5	16.8	9.0	276
8	6287174.190	922979.524	546712.821	15.1	11.5	7.1	226
9	6145058.482	1262078.912	1029289.949	14.4	14.7	8.1	220
10	6145058.472	1262078.922	1029289.966	15.2	18.8	9.9	242
11	6145058.461	1262078.959	1029289.982	14.7	11.9	6.2	272
12	6246471.242	820848.769	994267.959	14.8	10.7	6.6	254
13	6246471.242	820848.791	994267.980	14.8	19.0	9.7	212
14	6246471.245	820848.802	994267.997	11.2	9.2	4.4	90
15	6226097.286	275576.142	719121.718	12.5	9.7	6.5	250
16	6226097.288	275576.162	719121.725	12.8	9.9	5.8	264
17	6284298.292	827900.548	708988.616	16.7	15.0	7.2	252
18	6284298.292	827900.574	708988.628	15.4	16.4	8.9	242
19	6284298.284	827900.590	708988.655	12.9	17.2	6.2	215

2.2 ATTITUDE DETERMINATION ALGORITHM (ADA)

The ADA algorithm provides a fast and simple deterministic solution for the attitude of space craft system based on two vector observation generated from two different coordinate systems. ADA only accommodates two vector observations at any one-time instance (Bak, 1999). Initially ADA assumes that one of the vector measurements is more exact than the other. The vector measurements in the spacecraft body frame are named (b_2 and b_2), and the vectors in the reference frame (r_1 and r_2). It is assumed that the first vector measurement b_1 is the most reliable. Based on this three ADA is set up respectively as (Christopher, 2003).

$$t_{1b} = \frac{b_1}{|b_1|} t_{1r} = \frac{r_1}{|r_1|} \tag{1}$$

$$t_{2b} = \frac{b_1\ x\ b_2}{|b_1 x\ b_2|} t_{2r} = \frac{r_1\ x\ r_2}{|r_1 x\ r_2|} \tag{2}$$

$$t_{3b=\,t_{1b}}\ x\ t_{2b} t_{3r=}\ t_{1r}\ x\ t_{2r} \tag{3}$$

Finally, the equation 1–3were used to develop the ADA as;

$$A_{ADA} = [t_{1b}\ x\ t_{2b}\ x\ t_{3b}]\ [t_{1b}\ x\ t_{2b}\ x\ t_{3b}]^T$$

2.3 Development of an Adaptive Control System (ACS)

The development of adaptive control system was proposed to solve the dynamics problems experienced by the spacecraft. The adaptive control strategy focused employed artificial neural network solution which has the used data of the space craft dynamics to train and adjust the orientation of the system to the desired point. The data of the spacecraft collected spans out 35786km of space distance at 82 degrees east to the equator. The data was collected for training of the adaptive control system developed with Multi Layered Neural Network (MLNN). The MLNN algorithm was adopted from (Adetayo et al., 2018). The MLNN is made of weight, bias, activation function and training algorithm. The architectural model of the MLNN was presented as Figure 3;

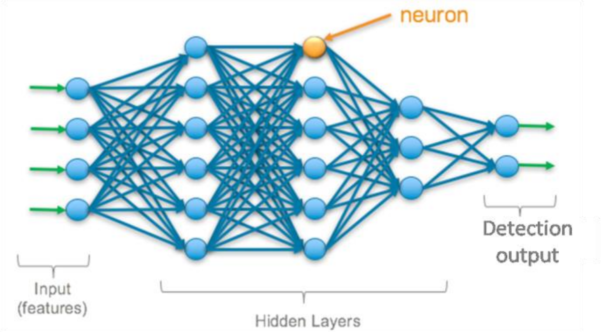

Figure 3: Architectural model of the Neural Network algorithm

The architectural diagram of the MLNN presented the two layered neural network model used to train the data collected. The number of inputs of the neural network is determined using the attributes of the dataset collected, while the activation function used is the tan-sig type. The training algorithm is the back-propagation type.

Training Flowchart of the MLNN

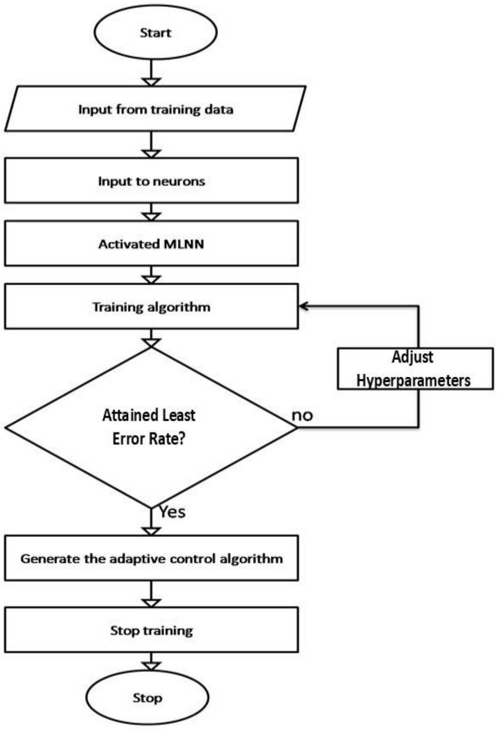

Figure 4: Training of the MLNN flow chart

The flowchart in the Figure 4 presented the work flow of the MLNN training process to generate the ACS algorithm. The data collected was loaded into the algorithm adopted and used to train the neurons by adjusting the hyper-parameters until the navigation patterns an orientation of the spacecraft is learned.

2.4 Development of the Adaptive ADCS

The ADCS was developed using the ACS algorithm generated in the previous section to model an improved ADCS for optimal satellite navigation. The ADCS was developed using the flowchart in Figure 5;

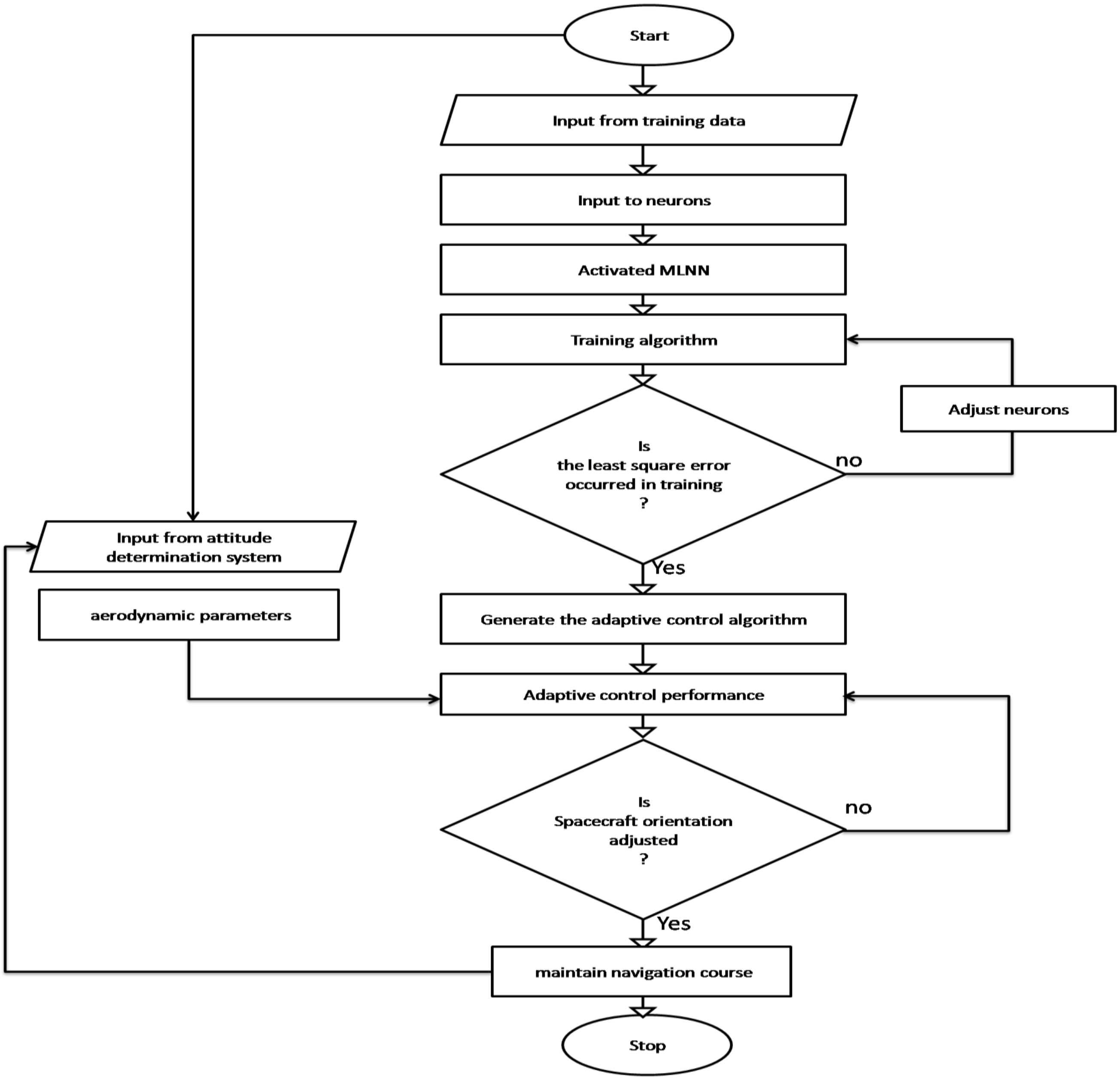

Figure 5: The flow chart of the adaptive ADCS

The flow chart was used to show the work flow of the adaptive ADCS developed. The trained algorithm was used to adjust intelligently the dynamic attitude of the spacecraft to achieve a desired attitude as shown in the architectural model in figure 6;

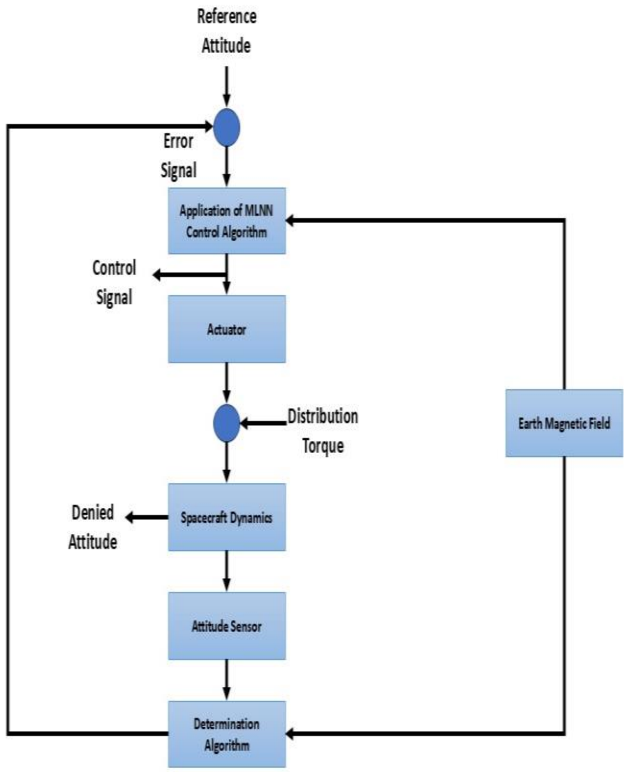

Figure 6: Architectural Diagram of the Adaptive ADCS

The Figure 6 presented the architectural diagram of the ADCS developed with the MLNN control algorithm developed. The sensors collected data of the space craft dynamics introduced due to torque disturbance and feed to the MLNN algorithm via the attitude determination system for training and correction of the error to ensure controlled navigation.

3. SYSTEM IMPLEMENTATION

The adaptive ADCS was implemented with Simulink. This was achieved with aerospace toolbox, control system toolbox and neural network toolbox. The neural network toolbox was used to train the data collected to generate the ACS and then used to configure the control system toolbox to develop the Simulink block of the ACS. The aerospace toolbox was used to implement the NigeriaSat-2 model and then control the dynamics with the adaptive ACS model developed.

4. SYSTEM RESULTS

To evaluate the attitude of the ACS developed with neural network, the MSE and Regression was used respectively. The idea was to measure the training error achieved in the neurons during the learning process and also determine the ability of the adaptive ADC algorithm to classify changes in the angular momentum and approximate to minimize the impact on the angular velocity. The MSE attitude is presented in Figure 7and the regression result in Figure 8;

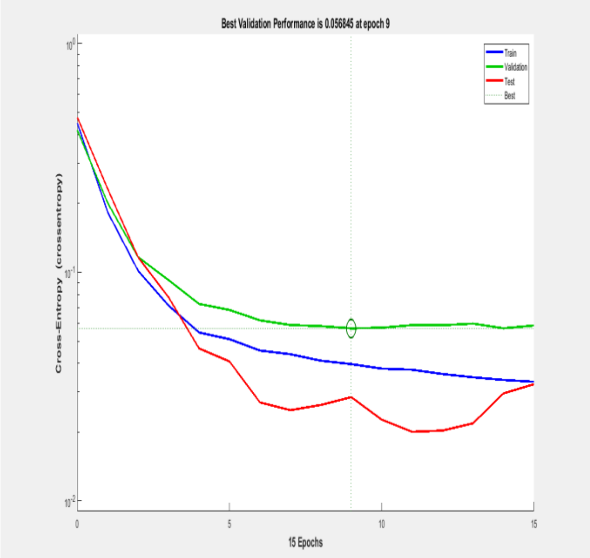

Figure 7: MSE result of the ADC

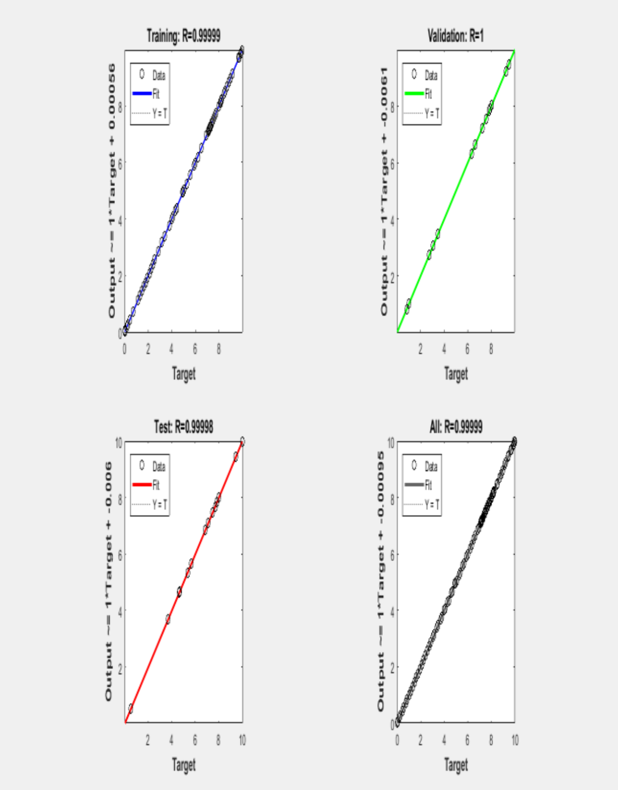

Figure 8: Regression Result

The Figure 7 and 8 presented the MSE and regression performance of the neural network-based ADC algorithm developed. From the result the MSE recorded is 0.056845Mu which is very good as it is approximately zero. The Regression also showed that the average R recorded from the training, test and validation set is 0.99999 which is approximately 1 and also very good. The results of the neuro algorithm developed for the spacecraft attitude control was validated with tenfold approach and the result are presented in Table 2;

Table 2: Result of Validation

S/N	MSE	Regression
1	0.056845	0.99999
2	0.077423	0.97884
3	0.024535	0.96556
4	0.028665	0.98892
5	0.042345	0.99294
6	0.037745	0.95737
7	0.042462	0.97444
8	0.054476	0.95837
9	0.034224	0.96496
10	0.055182	0.94569
Average	0.045394	0.97271

From the Table 2, the validation performance of the ADC developed was presented using MSE and regression and the average is 0045394Mu for MSE and 0.97271 for regression. The implication is that the neural network correctly learns the spacecraft data collected and was able to detect changes in the angular velocity. The step response of the control system is presented in Figure 9;

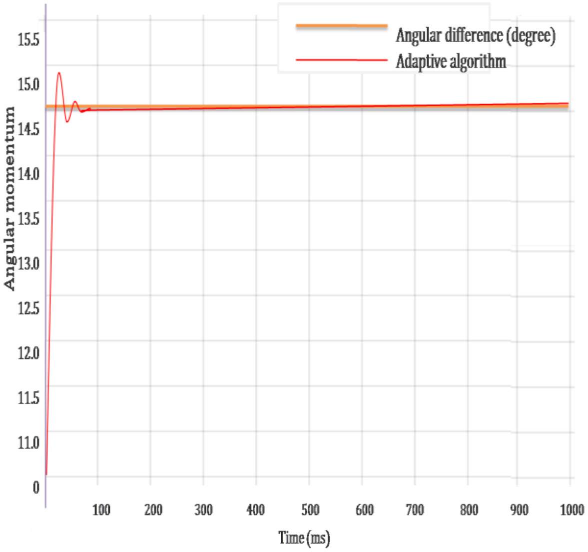

Figure 9: Step response of the adaptive ADC

From the Figure 9 it was observed that the adaptive controller was able to detect the dynamics in the spacecraft navigation and reduce the error in the angular difference. The adaptive ADC detects the dynamics in the angular momentum at 20ms and control at 91.24ms to maintain steady state in the navigation process. The total time of the attitude determination and control of the spacecraft is 111.24ms as against 465ms in the characterized which gives 76% reduction in decision time to control error due to dynamics.

4.1 Result of the Satellite Navigation

This section discussed the attitude of the satellite when simulated with the adaptive control system developed as the attitude control system. The impact of dynamics due to electromagnetic torque acting on the wheels momentum and the quaternion representation modelled in equation 1 and 2 is presented in Figure 10;

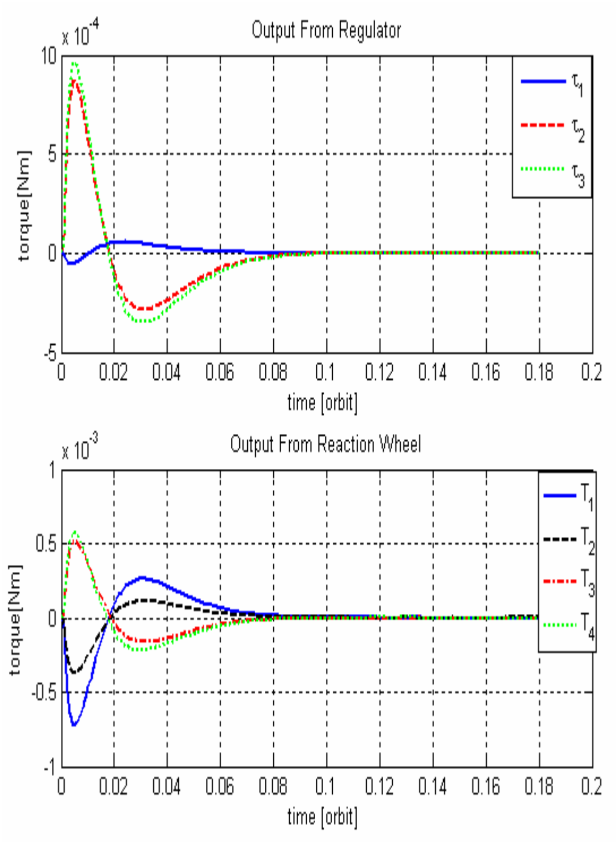

Figure 10: Impact of torque on the satellite

From the result in Figure 10, it was observed that nonlinear torque affected the momentum of the spacecraft orientation which reflected on the unstable orientation of the wheels based on the Euler rotational theorem, but was controlled at three orbits. This was due to the impact of the adaptive control system developed which was able to approximate the impact of the torque dynamics and stabilize the angular velocity as shown in the Figure 11;

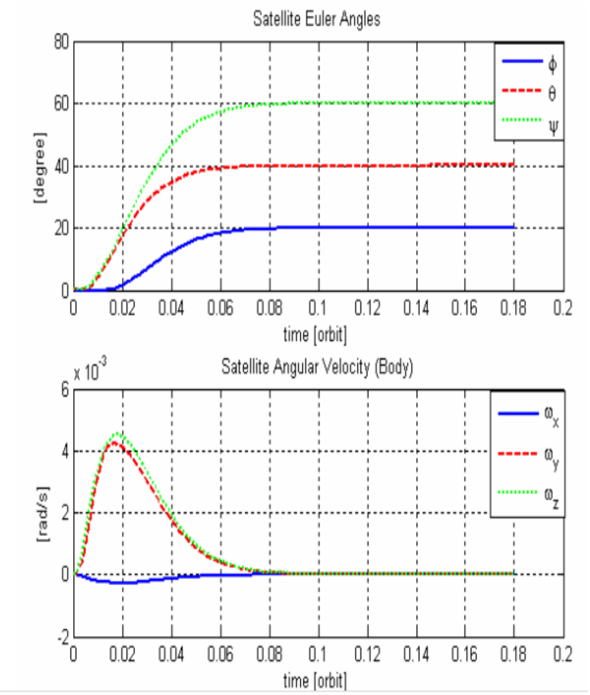

Figure 11: Result of the angular velocity

From the result it was observed that the impact of the dynamics torque affected the Euler angle position which results to error in the angular velocity as modelled in the Equation 4. However, this error was controlled by the adaptive control system developed and maintained stable orientation at 0.08orbit respectively. The implication of the result showed that the dynamic torque which affects the stable orientation of the spacecraft was controlled by the adaptive control system developed and was able to maintain stable satellite attitude.

4.2 System Integration

The system integration deployed the adaptive control system developed on the NigeriaSat-2 and tested on the space and the results recorded are presented in the Table 3;

The Table 3 presented the attitude of the satellite with the adaptive controller. The result showed the change in angular velocity and momentum on the satellite as it navigates along the equator.

Table 3: Result of System Integration with Adaptive Controller

Orbits	**X (m)**	**Y (m)**	**Z (m)**	X(mm)	y (mm)	z (mm)	**N**
	Orbital distance			**Error in angular velocity**			
1	6202492.807	822088.724	1225614.669	8.30	6.3	4.48	258
2	6202492.802	822088.756	1225614.687	8.40	9.8	5.32	221
3	6202492.792	822088.775	1225614.705	8.30	8.54	5.32	225
4	6211960.221	459265.512	1268115.070	8.40	6.3	4.34	257
5	6211960.228	459265.528	1268115.090	9.94	10.5	8.19	221
6	6211960.218	459265.558	1268115.115	8.68	10.7	4.34	250
7	6287174.200	922979.505	546712.811	10.15	11.76	6.3	276
8	6287174.190	922979.524	546712.821	10.57	8.09	4.97	226
9	6145058.482	1262078.912	1029289.949	10.80	9.8	5.67	220
10	6145058.472	1262078.922	1029289.966	10.57	13.16	6.93	242
11	6145058.461	1262078.959	1029289.982	10.80	8.09	4.34	272
12	6246471.242	820848.769	994267.959	10.36	10.7	6.6	254
13	6246471.242	820848.791	994267.980	10.36	13.3	6.97	212
14	6246471.245	820848.802	994267.997	7.84	6.4	4.4	90
15	6226097.286	275576.142	719121.718	8.75	6.5	6.5	250
16	6226097.288	275576.162	719121.725	12.80	9.9	5.8	264
17	6284298.292	827900.548	708988.616	8.96	8.09	4.98	252
18	6284298.292	827900.574	708988.628	10.78	11.48	6.23	242
19	6284298.284	827900.590	708988.655	9.03	12.04	4.34	215

5. CONCLUSION

The study successfully developed and implemented an Adaptive Attitude Determination and Control System (ADCS) capable of addressing the effects of dynamic torque on satellite attitude and stability. The ACS design's use of MLNN provided a dependable solution for real-time adaptation and correction of orientation errors, as evidenced by improved angular velocity control and stable satellite navigation during simulated operations. As part of the research methodology, data from the NigeriaSat-2 system at NIGCOMSAT was collected to evaluate the challenges with technical control and attitude. A Multi-Layered Neural Network (MLNN) for an Adaptive Control System (ACS) was trained using the data to simulate the spacecraft's dynamics. Despite dynamic torque interruptions, the MLNN-based ACS intelligently corrected and stabilised the satellite's orientation. The control system was placed on an optimisation testbed and assessed in a Helmholtz cage-created environment that mimicked a geomagnetic field.

The findings highlight how crucial adaptive control strategies are for improving satellite performance, especially when nonlinear disturbances like electromagnetic torque are present. This creative method ensures more dependable and effective space missions by laying the groundwork for future developments in satellite attitude control systems. In order to increase the system's durability and scalability for next satellite systems, more study could concentrate on increasing the adaptive algorithms' computational efficiency and testing the system in various environmental settings.

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